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Quench Problems of Nb_3Sn Cosine Theta High Field Dipole Model Magnets

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Abstract— **We have developed and tested several cosine theta high field dipole model magnets for accelerator application, utilizing Nb_3Sn strands made by MJR method and PIT method. With Rutherford cables made with PIT strand we achieved 10.1 Tesla central field at 2.2 K operation, and 9.5 Tesla at 4.5 K operation. The magnet wound with the MJR cable prematurely quenched at 6.8 Tesla at 4.5 K due to cryo-instability. Typical quench behaviors of these magnets are described for both types of magnets, HFDA-04 of MJR and HFDA-05 of PIT. Their characteristics parameters are compared on d_{eff}, RRR, thermal conductivity and others, together with other historical Nb_3Sn magnets. It is suggested a larger RRR value is essential for the stability of the epoxy impregnated high field magnets made with high current density strands. It is shown that a magnet with a larger RRR value has a longer MPZ value and more stable, due to its high thermal conductivity and low resistivity.**

Index Terms— **Nb_3Sn high field magnet, Quench, PIT, MJR, RRR**

I. Introduction

In the past several years we developed and tested several Nb_3Sn cosine theta model magnets, and their mirror magnets [1]. The earlier magnets were wound with Rutherford cable made of MJR strands, manufactured by Oxford Instruments Technology Ltd, which was the only commercially available high current density Nb_3Sn superconductor at that time for the high energy accelerator magnet. The quenches started prematurely mostly near or at the splice regions at the nominal operation ramp rate of 20 A/sec. With these magnets the premature quench was the main problem.

This year, using the recently improved PIT Nb_3Sn strands from ShapeMetal Innovation B.V., we made and tested a mirror magnet HFDM-03 and a regular cosine theta magnet HFDA-05 [2]. With these magnets, we achieved the current level of the short sample test data of the extracted strands [3]. The central field values B_0 of the HFDA-05 we achieved are 9.5 Tesla and 10.1 Tesla at the operation temperature of 4.5 K and 2.2 K respectively. With these magnets, the main problems are the training, probably due to the epoxy cracking and subsequent wire motion, and some degradation of the short sample data due to the cabling.

The importance of RRR for the stability of the Nb_3Sn magnets was reported at the Fermilab Workshop on Instability in April 2004 [4]. By comparing our results with the historically successful magnets, the causes of the quenches were investigated. The analysis of this problem is being worked out using a 3-D FEA by ANSYS.

II. Basic Parameters of Cosine Theta Dipole Magnets

The coil cross section of the cosine theta dipole magnet is shown in Fig.1. In this figure the flux distribution at 20 kA, corresponding to B_0 = 11 Tesla is shown. All coils of the tested magnets were wound with Rutherford keystoned cables made of 28 strands of 1mm diameter Nb_3Sn strands [5], [6].

The cosine θ magnet HFDA-04 and its corresponding mirror magnet HFDM-02 are wound with MJR strand cables, and the mirror magnet HFDM-03 and its corresponding cosine θ magnet HFDA-05 are wound with PIT strand cables. The major characteristics of these strands are summarized in the Table I.

The detailed characteristics of the magnets of both types of strands, including their power lead splice structure are reported

TABLE I. Typical Characteristics of 1 mm MJR and PIT Strands

	Deff	RRR	Ic (10T)	Ic (12T)	State	Tc(0,0)	No.of Subelements
MJR	110 µ	5	984 A	698 A	Virgin	18.3 K	54
PIT	50 µ	89	825 A	597 A	Extracted	18.3 K	192
NbTi						9.2 K	

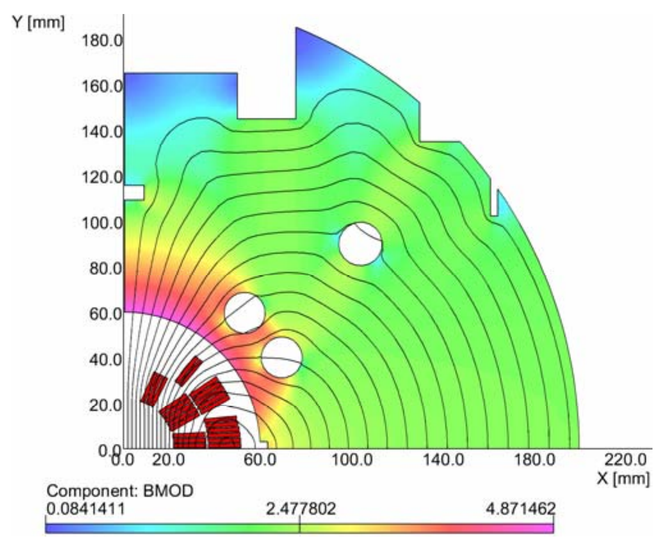

Fig. 1. Cross section of cosine theta magnet, shown with the flux distribution at

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20 kA, corresponding to 11Tesla.
in other reports [5], [6].

III. Quench Problems with MJR Magnets, HFDA-04 and HFDM-02

We have produced and tested several short cosine theta Nb_3Sn model magnets with MJR cables in the last several years. The most typical one is HFDA-04 [5] and its corresponding mirror magnet HFDM-02 [7]. Both HFDA-04 and HFDM-02 magnets were wound with keystoned MJR Rutherford cables. They have very low RRR values of 5 and 6, respectively. These magnets wound with MJR cables were quenching at a substantially low field, and showed similarly prematurely quenched near or at the splices at 4.5 K operation [8].

The cross section of the heat treated MJR Rutherford cable, is shown in Fig. 2, where the end of the cable is pictured. The most outside strand is pushed hard and flattened, and the next strand is really squeezed making a tear drop shape. The subelements at squeezed areas in these strands are seen damaged due to the cabling process. During heat treatment cycle, the inside pure tin melts and leaks out of the niobium mesh to the outside. The copper tubes surrounding the subelements were contaminated, and in worst case the overall copper stabilizer was contaminated, reducing the RRR to the order of 5.

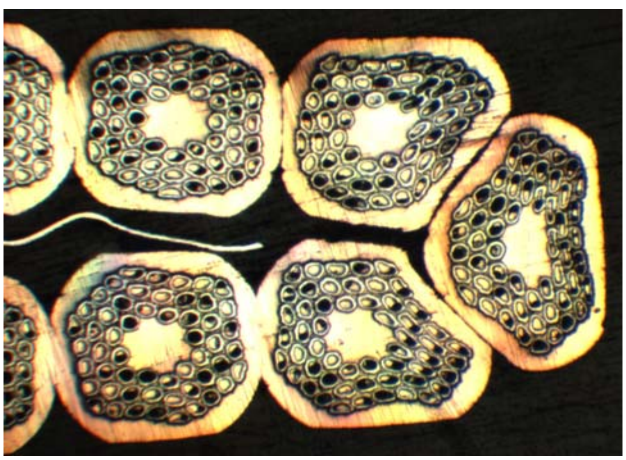


Fig. 2. Cross section of the heat treated MJR Rutherford cable. The subelements inside the end strand and the next neighbor strand are seen damaged. During the ramp-up of the heat treatment, the tin inside subelements leaked out and contaminated the copper stabilizer.

The HFDA-04 reached only 64 % of short sample data. All of the quenches started at the outer lead splice region at 4.5 K operation, regardless of ramp rate. When the magnet was operated at 2.2 K, certain quenches occurred at the inner splices regions [8]. This premature quench was also studied with consideration of flux jumping [9]. Its power lead splice is made of a Nb_3Sn cable, soldered with a NbTi cable and a copper cable.

The cable of the mirror magnet HFDM-02 had a stainless steel ribbon, and the magnet is assembled with a SS yoke not with an iron yoke. Its splice is made of a Nb_3Sn cable, which is sandwiched by two NbTi cables. This magnet quenched at the outer lead splices at 4.5 k operation, but when it was cooled to 2.2 K its quench starting points moved to the innermost coil block of the inner layer, at the highest field region. But still the quench current was quite low. The quench is caused by the thermal unbalance between heating and cooling of the system.

The splice is made of a Nb_3Sn cable, NbTi cable, and solder. The NbTi cable with a lower Tc value is more susceptible for starting a quench, if the splice is not well cooled.

A. Why LBNL RD3c Magnet Achieved 13 Tesla, While HFDA-04 Quenched Prematurely?

In the past few years Fermilab group always used 1 mm MJR strands for cosine theta magnets, except for the recent magnets made with 1 mm PIT strand cables. LBNL group has used 0.8 mm MJR strands for their RD3c magnet and obtained 13 Tesla [10].

While our highest B_0 field achieved was 6.8 Tesla with cosine theta magnets, they achieved 13 Tesla with RD3c Race Track dipole magnet using same MJR material. The difference between HFDA-04 and RD3c are shown in the following Table II.

Table II. Comparison between HFDA-04 and RD3c magnets

	Magnet type	B_{peak}	Strand	dia.	d_{eff}	Keystoned	RRR
HFDA-04	cosθ	6.8 T	MJR	1 mm	110 μ	Yes	5
RD-3c	race track	13.0 T	MJR	0.8 mm	88 μ	No	92/13/16

There is 20 % difference in d_{eff}, and there is a substantial difference in RRR values. It is partially due to keystoning of the HFDA-04 cable. The field distribution inside the conductor of HFDA-04 is rather uniformly high except in the outer layer region. But the field distribution of RD3c is rather localized, and it is peaked to the maximum field of 13 Tesla at the inside edges. If the field distribution has a big gradient in the cross section of a cable, there might be a chance of current sharing between strands.

IV. Quench Values of PIT Magnets, HFDM-03 and HFDA-05

After two years of collaborative effort with Fermilab, SMI succeeded recently to make and supply us their PIT strands, with reasonable degradation when made into Rutherford cables. Their 1 mm strand has 192 subelements, and its d_{eff} is 50 μm.

In April 2004, the mirror cosine theta magnet, HFDM-03, was excited up to 21 kA at 4.5 K and 21.8 kA at 2.2 K. This mirror magnet had a half coil (Coil-12), which was wound with a keystoned PIT Rutherford cable of 28 strands of 1 mm diameter. The peak field values in the cable were 9.75 T at 4.5 K and 10.0 T at 2.2 K respectively [2]. This mirror magnet (Coil-12) had an RRR value of 84.

In September 2004, the regular cosine theta dipole magnet, HFDA-05, (Coil-12 + Coil-13) was excited up to 16.93 kA, corresponding to B_0 = 9.5 T at 4.5 K, and up to 18.17 kA, corresponding to B_0 = 10.1 T at 2.2 K, both at 20 A/sec ramp rate. Considering the maximum field in the conductor is 5%

more, both cables of these two magnets reached the same short sample limit. The RRR value of the HFDA-05 is measured 113.

These quench current values are regarded near their short sample data of PIT cables. This high RRR values have contributed to the excitation up to the short sample test data current.

The Rutherford cables for HFDM-03 and HFDA-05 are keystoned with a compaction factor of 88.5 %. The cross section of this cable after heat treatment is shown in Fig. 3. There are some slightly damaged subelements inside the strands at the edge of the cable. But this may be tolerable for the magnet operation, but it is contributing to the degradation of the Ic value.

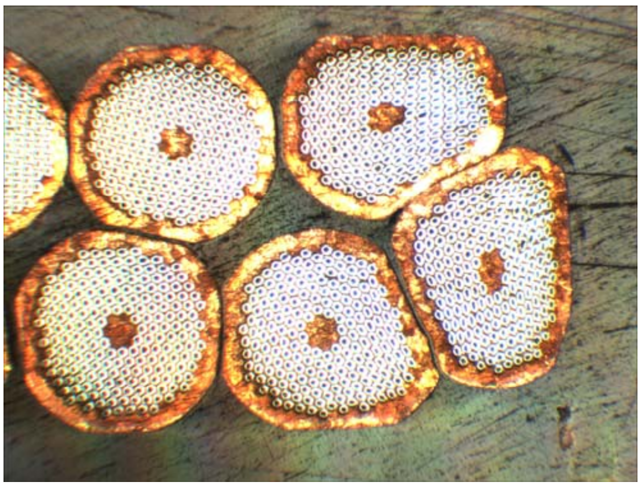


Fig. 3. Cross section of the heat treated PIT Rutherford cable. The brown spots on the copper stabilizer are due to the reflection from the large copper crystalline grain surfaces, indicating highly pure copper. There are some damages with some Nb tubes in the end strand.

Because the PIT strand uses $NbSn_2$ power in the Nb tubes and does not have pure tin as much as the MJR strand, there is much less chance of contamination during heat treatment. This is the advantage of PIT strand over the internal tin strand when using the Rutherford cable.

V. Training due to Epoxy Cracking

The training quench data of HFDA-05 are shown in Fig. 4. During the 4.5 K operation the first quench started from 14.0 kA and its 29th quench is in the flattened state at 16.8 kA range. It had about 17 % of excessive training range.

All of these quenches started from the inner most 3-turn block of the inner layer. The inner surface of the inner coil is directly exposed to liquid He. The inner surface showed a lot of cracking in epoxied surface even before testing. We think further cracking of the epoxy due to Lorentz force may be the main cause of the training of the magnet, thus inducing wire movement with heat generation.

To avoid the quench due to cracking of epoxy, we should avoid buildup of epoxy on the inner surface. In the future this excessive training should be eliminated. For instance, the CERN-ELIN magnet did reach 9.5 T at the second quench.

The cracking of epoxy on the inside layer surface has been observed also with our previous magnets, HFDA-04, HFDM-02 and others.

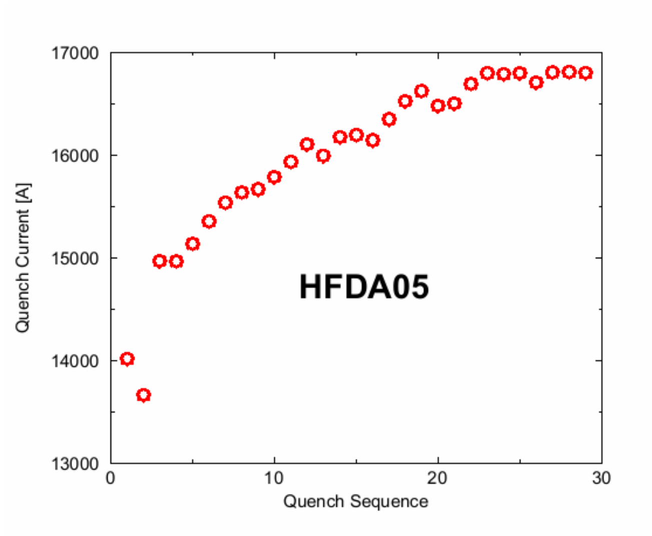


Fig. 4. The training curve of the HFDA-05 at 4.5 K at the ramp rate of 20 A/sec. It shows a substantial training, which started at 14 kA up to 16.8 kA.

VI. Simulation of Premature Quench near Splice Region of Low RRR MJR Magnets in Progress

A premature quench simulation of the MJR magnet, HFDA-04, is being developed, using a 3-dimensional ANSYS model of the splice region. When the RRR value of the strand is very low, it is very hard to recover from a quench, which is caused by a heat disturbance, by a flux jump, mechanical movement or others.

The resistivity of the copper of our Rutherford Nb_3Sn cables is shown in Fig. 5, for the case of RRR = 5 (corresponding to the MJR magnet, HFDA-04) and 80 (corresponding to the PIT magnet, HFDA-05) for the temperature range up to 120 K. The thermal conductance of the copper for these RRR values is shown in Fig. 6. As is shown, when the copper resistivity is increased with a smaller RRR value, the thermal conductance of copper is lowered. As can be expected from these curves, there will be a big difference between these cases in their cryo-stability. We are planning to get a quantitative criterion for the stability of this problem.

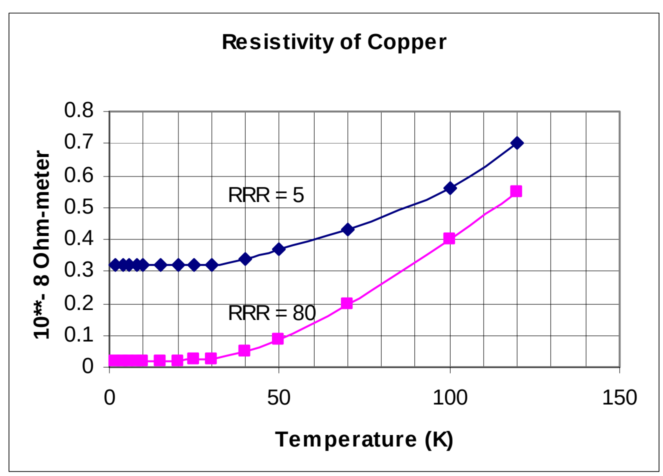


Fig. 5. Resistivity of copper for two different RRR values.

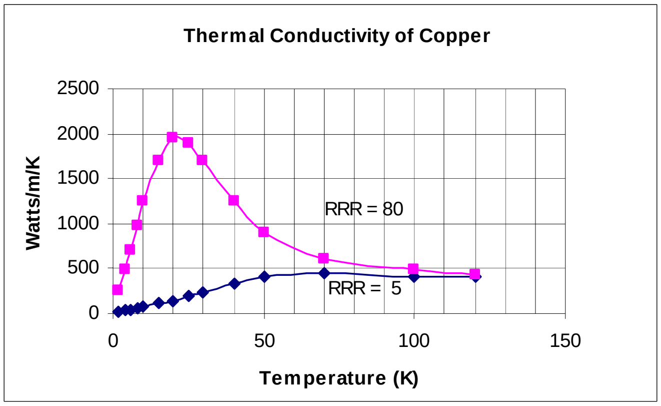


Fig. 6. Thermal conductivity of copper with different RRR values.

VII. Discussions

With the cosine theta dipole magnets wound with MJR cables, we always experienced premature quenches without reaching their short sample values. With the R&D magnets developed at LBNL, RD3c and HD1, they could excite their magnets up to the short sample data limit. Our cables are keystoned, while LBNL cables are rectangular and not keystoned. Probably the difference in RRR values; ours 5 to 6, while theirs above 13, made a difference. As pointed out before we can expect the RRR value will be important for the stability.

Consideration of a minimum propagating zone, MPZ is helpful to evaluate the stability of magnet [11]. MPZ is given for a superconductor with copper ratio r, as,

$$MPZ = \frac{r}{r+1}\sqrt{\frac{2k(\theta_c - \theta_0)}{J_c^{\,2}\rho}},$$

where θ_c is the critical temperature, θ_0 is the bath temperature, J_c the critical current, k and ρ are the thermal conductivity and resistivity of copper respectively. If the critical current is the same, MPZ is determined by the ratio of k and ρ. The RRR = 80 conductor should have about 15 times larger MPZ than that of the RRR = 5 conductor. Such a large difference in MPZ can explain the difference of magnet performance.

When the RRR value of the Nb_3Sn is very low, less than 10, the design of the power lead should be made very conservative, by providing enough cooling channels, by using two NbTi power lead cables and adding a copper heat sink to prevent the temperature rise of that part. Otherwise that part will start a quench due to flux jump because it is in the low field region. When the RRR value is large, 80 or so, just a single NbTi cable will work well.

VIII. Conclusion

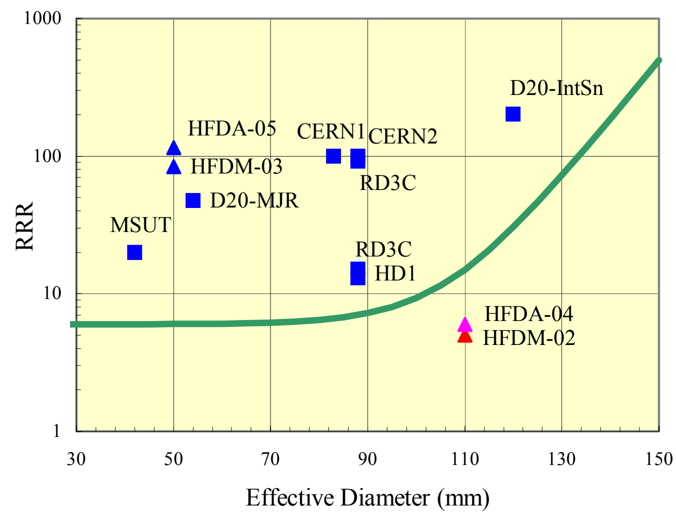
With the use of PIT strands, we could reach 10 Tesla field. Probably there are several reasons for this. Its small d_{eff} improved the stability of the strand due to the small value of flux jump energy. But more likely its higher value of RRR did improve the cryostability.

But there are still many things are to be improved. The magnets are showing extensive training. We think it is probably due to the cracking of the epoxy and wire motion. This problem should be fixed.

Our PIT cables show a large degradation partially due to cabling and keystoning. We have to improve these techniques, as well as we have to encourage the industry to make better Nb_3Sn strands for Rutherford cables.

For the stability of the magnet, it is now clear to have a strand with a smaller d_{eff} to prevent the effect of flux jump. At the same time we should have a bigger RRR value from the standpoint of cryo-stability. The MPZ of the conductor is strongly affected by the RRR value.

The correlation of d_{eff} and RRR value is shown in Fig. 7 with our magnets and the historical Nb_3Sn magnets [3]. We drew a line between the stable and unstable regions. This stability region should be studied further.



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